Opponent's report for the Doctoral Thesis of

Stefan Gohl
"Timepix Detector in Space Applications and Radiation Belt Dynamics Observed at Low Altitudes"

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In his Doctoral Thesis, the author Stefan Gohl investigates the influence of the solar wind on the dynamics of energetic particles in the radiation belts of Earth. Particles are analyzed with the Timepix Detector onboard the ESA Proba-V satellite in a low-Earth orbit. This technology, which allows to trace an energetic particle through the sensor matrix, is rarely used in space applications. The necessary steps for retrieving the particle species and flux are discussed. Particle fluxes obtained from Timepix are calibrated against and compared to simultaneous measurements from another particle instrument onboard Proba-V. The space-related part of the thesis is focused on five major geomagnetic storms, and on how they can be classified according to characteristic flux variations seen along geomagnetic L-shells crossing the radiation belts. Finally, solar wind parameters are correlated with observed particle fluxes from Proba-V and the Demeter spacecraft.

The thesis starts with a comprehensive summary of properties of the solar wind based on a magnetohydrodynamic description. Chapter 1 discusses the radially outward moving supersonic and super-Alfvénic solar wind plasma, the frozen-in solar magnetic field in the form of a Parker-spiral, and discontinuities and shocks driven by faster moving ejectas from the solar atmosphere. These are known as corotating interaction regions (CIRs) and interplanetary coronal mass ejections (ICMEs). Chapter 1 continues with the definition of a planetary magnetosphere, its large-scale configuration, a summary of current systems, and the phenomenon of magnetic reconnection, which plays a crucial role for the sequence of events happening during geomagnetic storms. The motion of single charged particles in a magnetic field is detailed in terms of the associated three adiabatic invariants (gyration, oscillation and drift). Together with potential sources and loss processes for energetic particles, they form what is known as the radiation belts. Chapter 1 finishes with an overview of mechanisms that can modify the configuration and composition of the radiation belts during disturbed times, i.e., during geomagnetic storms and substorms.

Chapter 2 introduces the Timepix Detector and its operating principles for measuring high-energy electrons, protons and heavier ions. Basically, this detector consists of a thin silicon layer in which incident energetic particles create electron-hole pairs along their paths through the silicon material. An applied bias voltage generates a current signal from those electron-hole pairs, which is directly related to the type and energy of the incident particle. After detailing the technical specifications and the different modes of operation for Timepix, Chapter 3 continues with the implementation of the *Space Application of Timepix based Radiation Monitor* (SATRAM) on the Proba-V satellite. SATRAM is considered as a kind of demonstrator technology, which shall augment particle measurements from another instrument onboard Proba-V, the Energetic Particle Telescope (EPT). Both data sets are compared in this thesis. As a third source of data, the Instrument for Detection of Particle (IDP) onboard the Demeter spacecraft is incorporated as well. Moreover, the author proposes a statistical method for identifying and removing noisy pixels from the Timepix data, concluding that those are unrelated to natural phenomena, but are entirely due to degrading of the sensor electronics.

Chapter 4 is about interpreting the raw data from Timepix. Three quantities are essential here: The shape of the particle's track, or cluster, which is left behind in the silicon medium, the maximum deposited energy along the track ("cluster height"), and the energy per track length ("stopping power"). Those three parameters are verified for electrons and protons in terms of numerical simulations (GEANT4 toolkit; SPENVIS online tool). Simulation results seem to be essential for interpreting the observations correctly. Three methods are presented for retrieving information on the particles: The Decision Tree Method, the Energy per Pixel Method, and a method based on a neural network (7 nodes, 2 hidden layers). It is found that electron fluxes are usually quite reliable when derived from Timepix frames that do not contain overlapping tracks, which is not true for the protons, because a significant fraction of protons are in fact electrons contributing as false positives.

In Chapter 5, it is shown how the particle counts are calibrated to flux values, and the various problems that go along with this procedure are thoroughly discussed, like including geometric correction factors, accounting for the production of secondary particles, backscattering and interrupted tracks. Low-occupancy frames, i.e., less than 20% of pixels in a frame are hit, are found to yield reasonable results for the fluxes. Medium occupancy frames (20% - 60% hits) rely on an approximate formula which seems to underestimate the true flux. For high-occupancy frames (60% - 90% hits), a flux determination is impossible. At least the Energy per Pixel Method can be employed to retrieve the ratio of electrons to protons. A comparison of average electron fluxes between SATRAM and EPT for the years 2015 - 2022 shows an overall good agreement. However, SATRAM fluxes are a bit noisier and often lower than EPT fluxes within one order of magnitude, especially for the range of <10 particles $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$. It is argued that this might be a consequence of a limited telemetry bandwidth and a smaller collective area for SATRAM.

Chapter 6 is devoted to a detailed analysis of five major geomagnetic storms that had a minimum D_{st}-index below -100 nT. As has been shown in Chapter 5, particle fluxes derived from Timepix measurements are surpassed in quality by those of EPT, which is why only data from EPT and the IDP instrument onboard Demeter are used here. A superposed epoch analysis indicates a grouping of storms into two categories, depending on characteristic variations of the average IDP electron flux (comprising energies of 70 keV - 2.34 MeV) around the time of D_{st}-minimum. These differences depend on both, the status of the radiation belts prior to storm onset, and the steepness of gradients in the solar wind parameters that are responsible for initiating the storm. The latter is investigated in more detail with another linear correlation analysis between changes in EPT electron fluxes and changes in the solar wind parameters (retrieved from OMNI database). For that, a larger data set including 31 interplanetary (IP) shock arrivals at Earth is studied. Results show that after storm onset, average fluxes of relativistic electrons tend to moderately decrease at $L > 4$, and to weakly increase at $L < 4$ (filling of the slot region). Fluxes in the inner belt do not seem to be affected by IP shocks. The found correlations confirm the classical picture that changes in the radiation belts are triggered by a dayside compression of the magnetosphere and magnetic reconnection at the magnetopause.

In the following is a short list of questions that emerged during reading the thesis, and which could be discussed further by the doctoral candidate.

- Presented results from the Timepix Detector are mainly based on the average flux of energetic electrons. Does Timepix also allow for a determination of particle energy and pitch angle? If not, why? And are there possibilities for improving the design of Timepix to achieve this goal?
- In Chapter 5 it is shown that electron fluxes from the Timepix Detector are systematically lower than those from the Energetic Particle Telescope (EPT) on Proba-V, especially for low fluxes ($<10\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$). This is surprising because Timepix should yield more accurate results in this range considering that these are made mostly of low-occupancy frames? Might this be due to a bias in the calibration procedure, e.g., an overestimation of the effective area, or of the factor c_{sec} (Eq. (5.5) in the thesis)? Could these parameters become a function of flux or energy?
- The two satellites Proba-V and Demeter are in a low-Earth orbit. Even if they are frequently crossing magnetic L-shells belonging to the radiation belts, they are not located deeply inside the radiation belts, like other missions as the Van Allen Probes or Themis (at least for the outer belt). Does this affect the conclusions drawn in Chapter 6 regarding the observed flux responses during geomagnetic storms?

The doctoral candidate, Stefan Gohl, is demonstrating with this well-written thesis that he possesses the necessary skills for performing independent and high-quality research. He obtained deep knowledge on the instrumental part of the Timepix sensor and its implementation on a satellite, as well as how to analyze the data with newly developed and original tools, and how to interpret the data in terms of complex radiation belt physics. Five first-author papers constitute a valuable contribution to this area of research, considering that the Timepix technology is rather new for space applications, and will become more common in the near future. I thus strongly recommend the present Doctoral Thesis by Stefan Gohl for defense.

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